HYPERSPECTRAL AND POLARIMETRIC REMOTE SENSING FOR THE CHARACTERIZATION OF FIRE PROCESSES FROM THE NASA ER-2 AIRCRAFT

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ABSTRACT

Biomass burning (BB) is a significant air pollution source, and BB emissions are composed of a complex mixture of gases and particles that may directly and indirectly affect both air quality and climate. There is a critical need to investigate the potential contribution of new-generation airborne remote sensing techniques for high-resolution, large-scale emissions and smoke plume development characterization in order to provide observational constraints on the dispersion of BB pollutants from landscape fires. Remote sensing from NASA's ER-2 high-altitude research aircraft can provide large-scale, high-resolution observations of fire temperature, plume rise, and characteristics of emitted gaseous and particulate pollutants. In particular, we focus on observations from the Hyperspectral Thermal Emission Spectrometer (HyTES), recently integrated on the ER-2, that produces a wide-swath thermal infrared (TIR) image with high spectral (256 bands from 7.5 to 12 μm) and spatial resolution (34 m from the altitude of the ER-2), and the Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) that acquires multiangular observations over a $\pm 67^{\circ}$ along-track range in eight (355, 380, 445, 470, 555, 660, 865, 935 nm) spectral and three (470, 660, and 865 nm) polarimetric bands with 10 m resolution from the ER-2. Using data from recent field campaigns including the Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC^{4}RS) and the Imaging Polarimetric Assessment and Characterization of Tropospheric Particulate Matter (ImPACT-PM), we demonstrate how hyperspectral thermal and multi-angle, spectropolarimetric remote sensing imagery can be used to constrain gaseous emissions and the particulate composition of smoke. We demonstrate that AirMSPI is able to quantify plume rise and BC content of smoke, while HyTES is able to quantify the fire temperature, as well as ammonia (NH_3) and methane (CH_4) emissions, even in the presence of smoke particulates. These capabilities are critically needed for constraining joint aerosol-gas emissions from fires, and for determining the impacts of smoke on local and regional air-quality. In order to translate these retrieval capabilities to space, we also investigate historical MISR, TES, AIRS, and IASI satellite observations collocated over different types of wildfires to quantify the relationships between fire emissions of gases, especially NH_3, and primary and secondary aerosol production as a function of combustion type and ambient atmospheric conditions. Our results highlight the potential benefits of future joint analysis of particulate and gaseous emissions from the same BB plume with the HyTES and AirMSPI instruments flying together on the ER-2 platform, and utility of such collocated observations for improving our understanding of BB aging processes.

***Index Terms*—** HyTES, AirMSPI, Fires

1. INTRODUCTION

As the frequency and size of fires in the Western United States and their potential effects on human populations grow, a more comprehensive understanding of the fundamental coupling of weather, fuels, and topography with respect to fire emissions becomes essential. Therefore, the overarching science goal of high-altitude airborne remote sensing observations is to provide critical, process-level understanding of the connection between fire temperature, plume dynamics, and the emission and downwind dispersion of gases and particulate matter to improve fire modeling systems and predictions of pollutant impacts on air quality and human health. While airborne *in situ* and ground-based measurements have been used effectively at small scales to constrain fuels, plume dynamics, and emissions, such observations cannot provide the larger-scale characterization needed for landscape fire applications. While satellite observations provide the large-scale context, the subset of fires amenable to retrieval from satellite are outside the realm of most controlled burn experiments and are too large to be effectively measured from towers or tethered balloons for process-oriented studies. In order to establish a quantitative chain of verification from laboratory and airborne *in situ* measurements of emissions to satellite observations, an intermediate step of medium-scale (both spatial and temporal) remote-sensing observations is required, which flight campaigns have yet to collect.

Our concept utilizes imaging spectrometry, and multi-

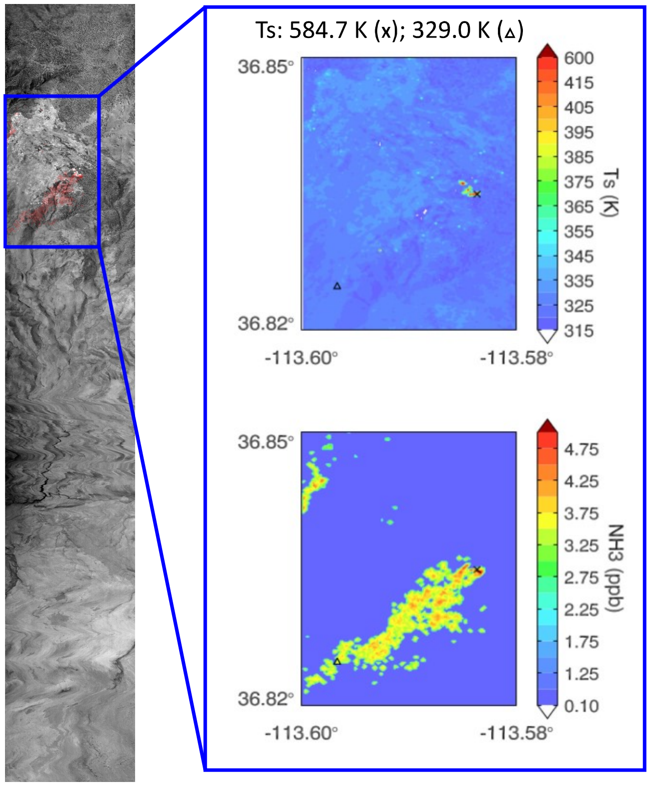

Fig. 1. HyTES retrievals of the surface (skin) temperature and NH_3 enhancements over the Gulch fire observed on July 3, 2014. The upper image is the retrieved surface temperature. The lower figure shows retrieved NH_3 plume originating from the fire pixel.

angle spectro-polarimetric remote sensing to characterize spatially-and-temporally resolved (∼30 m, ∼20-minute scale) biomass burning plume evolution for wildfires.

2. HYTES

The NASA HyTES instrument, built and managed by the Jet Propulsion Laboratory (JPL), is a pushbroom imaging spectrometer with 256 spectral channels between 7.5 and 12 μm, which yields a spectral resolution of ∼17.6 nm [1, 2]. The imager has 512 pixels across track, resulting in a swath width of about 1 km for a flight altitude 1 km above ground level (a.g.l.), and a pixel size around 2 m $\times$ 2 m. The pixel size and swath width increase proportionally with the flight altitude.

The instrument's high resolution thermal infrared spectra enable the qualitative detection and mapping of several important trace gases that affect climate and air quality, including methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) [2, 3]. The HyTES Level-2 (L2) data products include the land surface temperature (T_s) and spectral emissivity data for each flightline that is shown to be sensitive to to relatively low temperatures of smoldering fires. The flaming and smoldering phases of combustion have different emission factors for all aerosol and gaseous species [4, 5], and it was demonstrated recently that the larger amount of NH_3 is known to be emitted during smoldering periods and for low-temperature fires [6].

Recently we developed more computationally expensive *quantitative* retrieval of NH_3 from HyTES observations of small-scale ammonia sources, including small fires. The approach was adapted from the TES retrieval algorithm [7] by accounting for the spectral and spatial resolution of the HyTES instrument, in a manner similar to the way the CH_4 retrieval was developed [3]. The algorithm is currently under validation, however the initial uncertainty estimates suggest $\sim$ 50% retrieval uncertainty at the bottom layer decreasing to $\sim$ 20% retrieval uncertainty moving up in the profile. The total error is primary attributable to a priori constrains. Figure 1 shows an example of the retrieved surface temperature and NH_3 concentration from the fire emission for the case of HyTES observations over Gulch fire in Arizona collected from the 2 km altitude on July 3, 2014. The detected high surface temperature above 350 K indicates the position of the fire. The thermal contrast of the burning area $\sim$ 40 K was sufficient to perform the retrieval. The estimated burning area is about 150 m by 100 m and is too spatially small to be resolved in the current satellite observations. The elevated NH_3 plume starts at the fire location, and the outflow of the emission extends to the downwind side for roughly 1.5 km (120 $\times$ 12 m = 1500 m). The maximum enhancement about 5 ppb is found near the burning area and gradually decreases with distance from the source.

HyTES has had a number of successful flights on the ER-2 aircraft (20 km, 35 m pixel), that will allow data acquisition over more spatially extensive regions to increase chances of detecting, imaging and characterizing low-intensity smoldering fires. The theoretical sensitivities indicate the similar algorithm performance for the high-altitude observations as for the HyTES observations from $\sim$ 2 km altitude.

3. AIRMSPI

NASA AirMSPI instrument, built and managed as a joint effort of the Jet Propulsion Laboratory (JPL) and the University of Arizona, is an eight-band (355, 380, 445, 470, 555, 660, 865, 935 nm) pushbroom camera, measuring polarization in the 470, 660, and 865 nm bands, mounted on a gimbal to acquire multiangular observations over a $\pm 67°$ along-track range. [8]. AirMSPI has been flying aboard the NASA ER-2 high altitude aircraft since October 2010, and has participated in many field campaigns collecting data over the polluted areas of the California Central Valley and the Southeast US. The AirMSPI instrument was proven to have a high sensitivity to aerosol optical properties with $\sim$ 0.015 uncertainties in aerosol optical depth (AOD) and $\sim$ 0.03 in single scattering albedo (SSA) as compared with ground-based validation

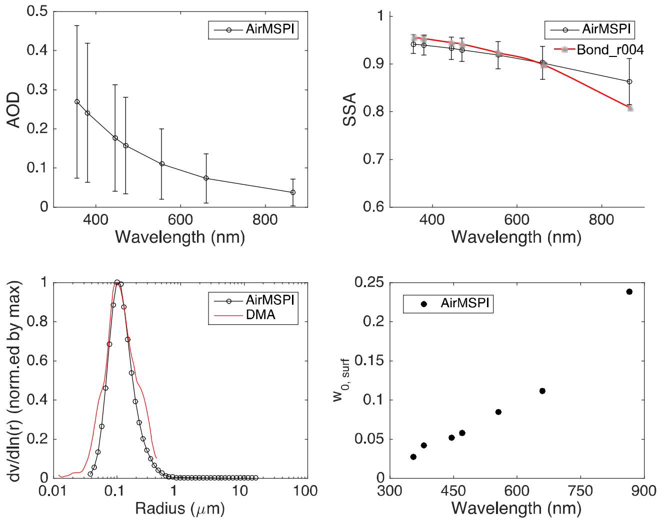

Fig. 2. AirMSPI retrieved aerosol and surface properties averaged over the 10 by 10 km AirMSPI footprint over the Fort Fire in Lebec, CA observed on July 8, 2016. The error bar shown on AOD and SSA retrievals retresents the aerosol property variability in the smoke plume. (a) AirMSPI AOD, (b) AirMSPI retrieved SSA plotted together with SSA derived from SP2 observations under assumption of BC refractive indices as described in [11], (c) AirMSPI retrieved size distribution plotted together with an averaged size distribution measured by the DMA instrument, (d) AirMSPI retrieved surface reflectance.

datasets over both ocean [9] and land [10] targets.

Recently, we demonstrated the value of multiangle polarimetric observations for the Black Carbon (BC) content using AirMSPI spectro-polarimetric radiances collected over the Fort Fire in Lebec, CA[11] during the ImPACT-PM field campaign. The campaign was a joint Jet Propulsion Laboratory (JPL) and California Institute of Technology (Caltech) study, supported by NASA, was conducted to evaluate the ability of multiangle, spectro-polarimetric remote sensing to retrieve information on the distributions of atmospheric particle types, with emphasis on carbon-containing compounds (BC and OC).

In situ measurements of aerosol particle size, composition, and optical properties during the ImPACT-PM were made aboard the Navy CIRPAS Twin Otter aircraft, using an SMPS, AMS, SP2, PSAP, and nephelometer. The SMPS, consisting of a differential mobility analyzer (DMA) coupled to a condensation particle counter (CPC; TSI model 3010), measured particle size distributions between 15 and 1000 nm diameter every 90 sec. The instrument description can be found in Table 1 of Kalashnikova et al. 2018 [11]. The example of AirMSPI retrievals over the Lebec fire in comparison with collocated in-situ data from Differential Mobility Analyzer (DMA) and Single-Particle Soot Photometer (SP2) instruments are shown on Fig. 2.

Using collocated observations from remote sensing and in-situ instruments that were deployed in the ImPACT-PM campaign, we determined that the polarimetric sensitivity of AirMSPI instrument to BC mass fraction has uncertainty of $\sim$5% in BC mass fraction at an AOD of 0.33 at 470 nm. That corresponds to polarimetric uncertainty of $\sim$0.04 in SSA, in agreement with previous polarimetric sensitivities to SSA over the land [10].

4. DATA SYNERGY

Thermal infrared spectra provides unique information needed to simultaneously characterize land surface temperature and atmospheric ammonia enhancements including those produced by small-scale agricultural, industrial, and biomass burning sources. In addition, high-resolution detection and quantification of NH_3 over non-persistent sources like wildfires from HyTES shows that the instrument is a powerful tool that can be used to improve regional scale fire emission inventories by accounting for the presence of temporally short NH_3 processes. Because TIR wavelength of spectrometers are much larger than the size of aerosol particles in the smoke, particulate scattering from smoke has little effect on the thermal signal. This suggests potential for combined analysis of both the particulate and gaseous emissions from fires by flying HyTES with AirMSPI instruments on the high-altitude ER-2 aircraft to maximize spatial coverage and increasing the change of fire detection. AirMSPI retrievals of aerosol properties could be used to evaluate emission and evolution of aerosol particles in the smoke and quantify BC content (fraction of BC mass concentration) and the relative contribution organic, non-organic and BC aerosols, while HyTES could provide information on concentrations of gaseous enhancements and the land surface temperature of smoldering fires that are particularly productive in terms of NH_3 emissions. Synergistic use of hyperspectral thermal, multiangle polarimetric observations would help simultaneously characterize NH_3 enhancements and particulate composition of smoke to determine fractions of primary and secondary aerosol contributions to help constrain air-quality models.

Another interesting synergy that could be very helpful for fire characterization is combine use of hyperspectral observations that cover spectra from VIS to TIR [12]. Because the peak of the Planck Function is moving toward shorter wavelengths with an increase of the fire temperature, hyperspectral observations in VSWIR spectral region are sensitive to very high temperatures. Hyper-spectral observations in VSWIR could be used for temperature retrievals of hot flaming fires up to 1500K [13]. The MIR and TIR spectral regions, in contrast, are more sensitive to lower temperatures between approximately 300 and 800 K, and are better suited for cooler smoldering fires. The combined use of hyperspectral VSWIR, MIR, and TIR data thus offers opportunities to better characterize the full range of fire burning conditions.

5. ACKNOWLEDGEMENT

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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